Extensive Renovation of Heritage Buildings - Reduced Energy Consumption and CO_2 Emissions

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Abstract: In the debate on whether or not heritage buildings should be included in work to mitigate climate change impacts, it is important to assess the impact of these buildings. Therefore the results of an extensive energy upgrading of a listed complex was studied. Climate change and measures to mitigate its effects have been a global priority for more than a decade. Efforts to mitigate climate change have focused on reducing greenhouse gas emissions, especially CO_2. As a consequence, there is an increased interest in reducing the energy consumption and increase the indoor climate standard of many existing, older and heritage buildings. However, heritage buildings possess heritage values that need to be protected while on the other hand the buildings need to remain part of the attractive building stock, as many of these buildings will otherwise deteriorate. Based on an example, this paper identifies feasible energy-upgrading measures for implementation including measures to provide an acceptable indoor climate. The energy savings as well as the reduction of CO_2 emissions are calculated. Furthermore, it is discussed how measures can affect the durability of a heritage building, as measures may create a far more vulnerable building and change its robustness to withstand moisture and user behaviour.

Keywords: Case study, climate mitigation, energy upgrade, heritage buildings, renovation.

1. INTRODUCTION

Climate change and measures to mitigate its effects has been a global priority for more than a decade. On a global priority scale, efforts to mitigate the impacts of climate change have focused on reducing greenhouse gas emissions within the framework of the Kyoto Protocol [1], which was implemented partly on an international level and partly through individual national initiatives. Efforts to mitigate climate change have focused on reducing greenhouse gas emissions with emphasis on reducing the CO_2 emissions. In many countries, buildings using energy for heating and comfort are one of the two principle energy-consuming sectors and therefore there is a great interest in reducing buildings' CO_2 emissions either by reducing their individual energy demand or by providing a CO_2-neutral energy supply. Traffic is the second principle energy consuming sector, in Denmark each sector being responsible for approx. 40% of the energy consumption. Reducing the amount of energy used for heating and comfort provides an opportunity to produce less energy or to use the saved energy for other purposes. Over the last decade, requirements to the indoor climate and the energy demand of new buildings have gradually been tightened in many countries. These tightened requirements were introduced in order to reduce the energy consumption for heating and comfort and consequently reduce their CO_2 emissions [2]. This means that existing, older and especially heritage buildings are categorized to have a very high energy demand as well as a very low indoor climate standard compared with today's requirements, particularly when it comes to an acceptable indoor climate. Therefore, there is an intensified interest in introducing energy-saving measures in many existing buildings, older buildings and heritage buildings. However, many existing buildings and heritage buildings have restrictions that protect the entire building or parts of it. Especially listed buildings possess heritage values that need to be protected. On the other hand, these buildings need to remain part of the attractive building stock, as the buildings will otherwise deteriorate since there is no financial basis for maintaining them [3]. Only if the owner has a particular interest in the building, e.g. for cultural or sentimental reasons, he might be interested in maintaining a loss-making building. To assess the impact of heritage buildings in relation to mitigating the impacts of climate change, this paper describes a case where extensive energy upgrading of a listed complex was carried out with respect for its heritage values. The paper focuses on the reduction of energy consumption by implementing measures for the energy upgrading of the complex, which includes four listed buildings and a courtyard. The case study of the complex provides calculated quantities for the reduction of CO_2 emissions in relation to the energy upgrading of the individual heritage buildings while ensuring an indoor climate that complies with the applicable guidelines and directions issued by the Danish Working Environment Authority[1], without compromising

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[1] Danish Working Environment Authority, (Arbejdstilsynet in Danish). The agency is an agency under the auspices of the Ministry of Employment. The agency is the authority which contributes to the creation of safe and sound working conditions at Danish workplaces. This is done by carrying out inspections of companies; drawing up rules on health and safety at work; providing information on health and safety at work. The agency has author-

identified heritage values. The paper discusses the feasibility of energy-saving measures as well as requirements and control levels for the indoor climate necessary to protect extensively energy upgraded heritage buildings.

The measures were only feasible when they agreed to create synergy between the interests in preserving heritage values and the development of affordable energy upgrading that was compatible with the requirements for the future use of the building. The listed complex is a case study where the Heritage Agency[2], the Danish Working Environment Authority and the owner as a team cooperated in identifying feasible energy-upgrading measures. During the process, the owner was supported by architects and engineers. The case study includes restoration, energy upgrading and renovation of the individual buildings that constitute the listed complex.

2. DESCRIPTION OF THE COMPLEX

The listed complex, *Fæstningens Materialgård*, located in the western part of downtown Copenhagen, was used as case for the study. The history of the listed complex goes back to the 17th and 18th centuries when the old royal materials yard had to be replaced by a new one. Construction of the complex begun in 1740 with a new, very distinguished residence for the supervisor. The complex consists of four individual listed buildings. The buildings form a single complex surrounding a courtyard, see Fig. (**1**) and consist of 1 to 3 storey brick buildings with red tile roofs, yellow lime-washed facades, green-painted doors and gates and white-painted windows. Only the original warehouse building of the complex is built as a half-timbered structure.

The use of the individual buildings of the complex has changed several times in the course of their history. Recently, the buildings were used for different office-type functions. The buildings and the courtyard area have a listed status. This listing is based on the Danish Act on Protecting Buildings and the Conservation of Buildings and the Built Environment [4], which means that all building work, beyond routine maintenance, requires a permit from the Heritage Agency.

In 2007, the condition of the listed complex was examined. The examination showed that the complex had been strongly affected by many refurbishments of the buildings which had been carried out over the years and which had not respected the values of the listed complex. However, it does not appear to have caused serious damage to the main structures including settlement of the foundations.

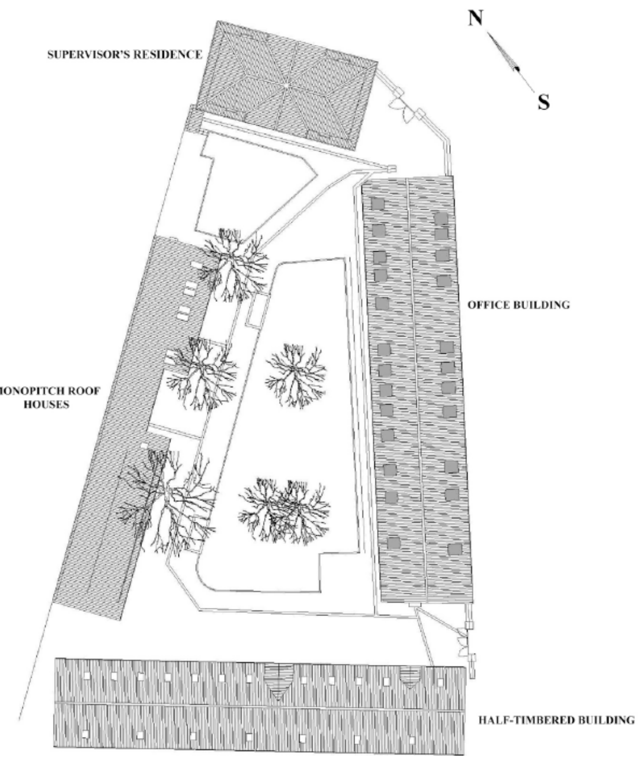


Fig. (1). Site plan of the listed complex, *Fæstningens Materialgård*.

In accordance with the method described in ISO 9972: 2006 [5], a building envelope permeability test was carried out as a blower door test done on the buildings prior to the energy upgrading and it showed large concentrated leaks in the building envelope. As well as resulting in a large heat loss, these leaks also caused indoor climate discomfort in the form of draughts and asymmetrical temperature distribution in the individual rooms in the buildings. To establish an airtight building envelope was one of the main energy-upgrading measures.

The owner wanted to renovate and upgrade the complex to a standard that would make it attractive for offices, conference and meeting facilities, i.e. having a good indoor climate. At the same time, the energy consumption should be reduced without compromising the heritage values of the complex. Each building in the complex has fundamental heritage values.

2.1. Supervisor's Residence

The supervisor's residence, see Fig. (**2a & 2b**), is recognised by its representative character and position in the hierarchy of the complex, the hierarchy between the storeys, the rooms and interiors with a mix of historic styles and joinery details. The supervisor's residence is characterised as the 'grandest' building in the complex, and there is a desire to expose and enhance the fine, richly decorated interiors.

2.2. The Half-timbered Building

The still-preserved half-timbered building, see Fig. (**3a & 3b**), retains its warehouse character and clearly shows the longitudinal beam structure and rough, simple detailing. The character of the half-timbered warehouse with its clear structures and rough simple detailing, as well as its close relation-

ity to penalise enterprises which do not comply with the working environment rules. As regards clear violations of the substantive rules of the Working Environment Act, the agency has the power to issue administrative fines. In cases of extreme danger, the agency may also order the work to be suspended. The responsibilities of the Danish Working Environment Authority are based on the Working Environment Act and related Executive Orders. Postboks 1228. 0900 København C. Denmark. Located 2014.05.06 at: http://arbejdstilsynet.dk/en/engelsk.aspx.

[2] Heritage Agency, Danish Agency for Culture. (Kulturstyrelsen in Danish). The agency carries out the cultural policies of the Danish government within the visual and performing arts, music, literature, museums, historical and cultural heritage, broadcasting, libraries and all types of printed and electronic media. H.C. Andersens Boulevard 2. 1553 Copenhagen V. Denmark. Located 2014.05.06 at: http://www.kulturstyrelsen.dk.

ship with the courtyard, is to be emphasised and strengthened through the renovation.

a)

b)

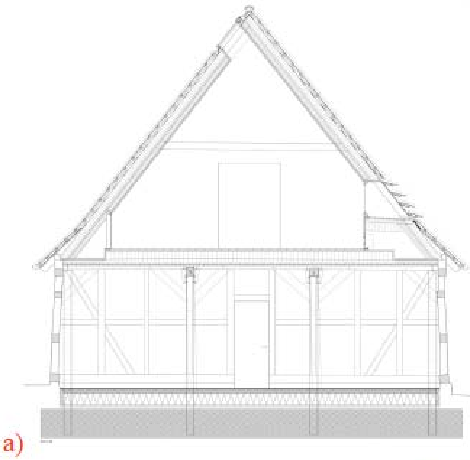
Fig. (2). The building containing the supervisor's residence. **a)** The structural section, **b)** a photo of the supervisor's residence after renovation.

2.3. The Office Building

The office building is recognised for its longitudinal partition walls, the distinction between the northern and southern parts of the building, its room plan layout and joinery details, see Fig. (**4a & 4b**). The renovation of the office building was undertaken to re-establish valuable elements from different periods and to restore the old room structures.

2.4. The Monopitch Roof Building

The monopitch roof building, shown in Fig. (**5a & 5b**), shows the original timber structure with very large dimensions. Renovation of the monopitch roof building was undertaken to re-establish the characteristics of the buildings as more or less open 'sheds' with clear structures, few simple details and a close relationship to the courtyard.



a)

b)

Fig. (3). The half-timbered building. **a)** The structural section, **b)** a photo of the half-timbered building after renovation.

3. INITIATED ENERGY-SAVING INITIATIVES

Individual feasible energy-upgrading measures for each building in the listed complex are shown in Table **1**. Measures were agreed through a process of selecting feasible comprehensive renovation measures, including energy-upgrading measures for heritage buildings. The process depends on the cooperation between authorities and the owner of a heritage building. It can lead to the identification and implementation of feasible measures for renovation, including energy-upgrading, that allows the preservation of identified heritage values inherent in a listed building or a listed complex. The process is outlined and described by Rasmussen [6]. The individual measures as well as the entire project need to comply with requirements in terms of:

- conservation and heritage
- cost-benefit, including rental opportunities, operation and maintenance
- architecture, including appearance, functionality and interior design
- structural design, including risk assessment and building physics
- energy, CO_2 and indoor climate

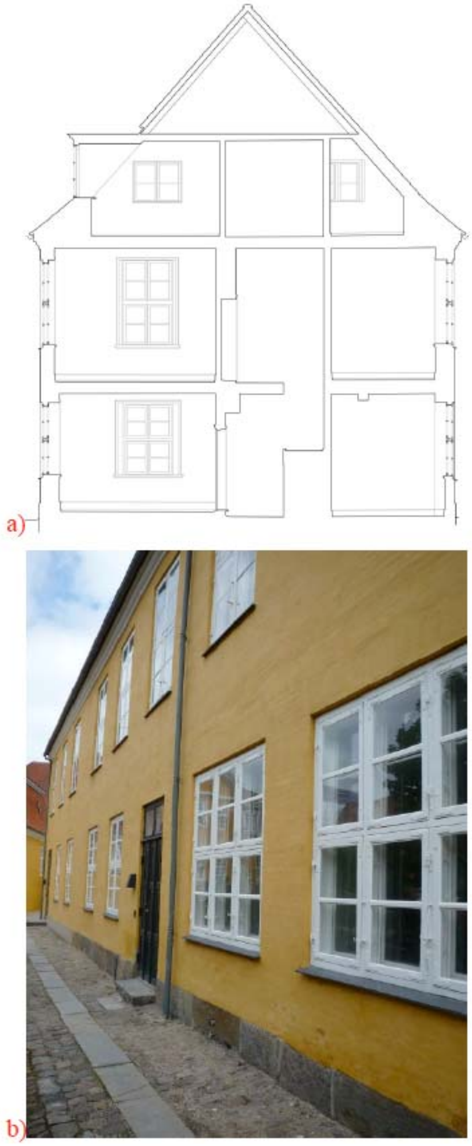


Fig. (4). The office building. **a)** The structural section, **b)** a photo of the office building after renovation.

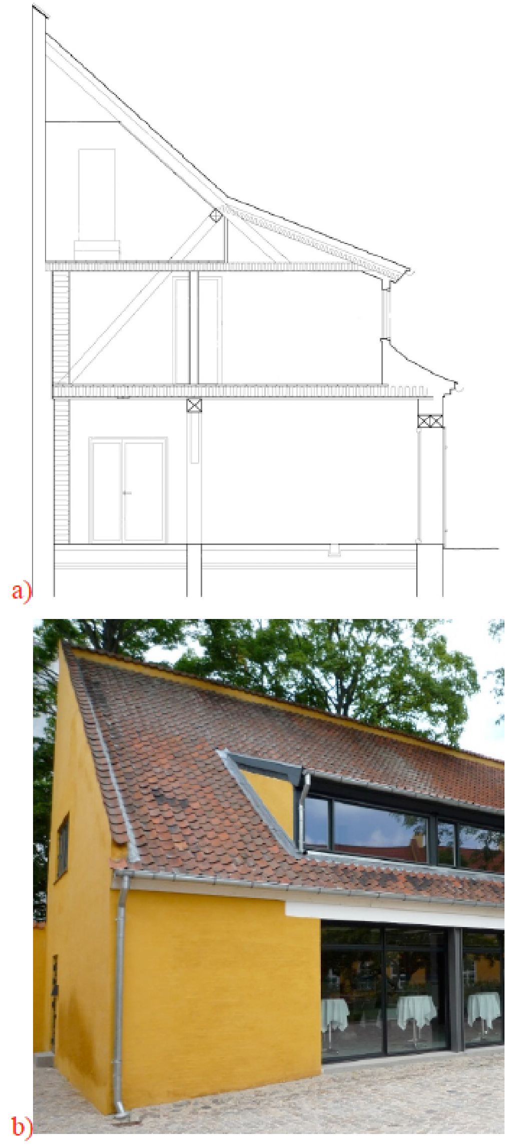


Fig. (5). The monopitch roof building. **a)** The structural section, **b)** a photo of the monopitch roof building after renovation.

4. CALCULATION METHOD

A model was built up for each building in the complex. The model was used to calculate the energy demand of each building by means of a PC program, BE10[3], which is in effect an integral part of the Danish Building Regulations and consequently an important part of the implementation of the Directive on the Energy Performance of Buildings, EPBD in Denmark. The calculations were made in accordance with the mandatory calculation procedure described in Energy Demand of Buildings, a guideline published by the Danish Building Research Institute [7]. The software uses the mandatory calculation core also developed by the Danish Building Research Institute for analyzing buildings and installations.

A base model was built up based on the existing conditions of the individual buildings and made consistent with the measured consumption data. To ensure a reliable model, the base model was built up with the existing interior layout and occupant loads and then compared with the previous five years' consumption of water, heating and electricity. This model was used as base. Reference models were built up and adjusted to the new design with the new interior layout and with the future occupant load. Calculations were made for the individual buildings before and after the implementation of energy-upgrading measures. These models were used as references.

Calculations were made using the reference model to calculate the impact of the individual feasible energy-upgrading measure agreed for each individual building. The calculated heat balance was calculated and was based on the future interior layout and occupant load, while maintaining a thermal environment at a Category C level [8], see Table **2**,

[3] BE10 is a PC program that calculates the energy demand of a building, which in effect is an integral part of the Danish Building Regulations and consequently an important part of the implementation of the EPBD in Denmark. Located 2014.04.30 at: http://sbi.dk/be10

Table 1. Feasible measures for the energy upgrading of the individual buildings in the listed complex.

Measure	Supervisor's residence	Half-timbered building	Office building	Monopitch roof building
Low-energy glazing – 3 mm glass set in the existing secondary frames	✓		✓	
New windows with low-energy glazing in new window openings		✓		
Low-energy glazing in the existing secondary frames, where possible		✓		✓
Replacement of windows, that are not original, with new windows with low- energy glazing				✓
New low-energy windows in new window openings (re-established gateways)				✓
Building envelope air permeability (0.5 h^{-1} in the basement, 0.2 h^{-1} on the ground floor and 0.2 h^{-1} on the first floor)	✓			
Building envelope air permeability (0.5 h^{-1} on the ground floor and 0.16 h^{-1} on the first floor)		✓		
Building envelope air permeability (0.29 h^{-1} on the ground floor, 0.2 h^{-1} on the first floor and 0.2 h^{-1} on the second floor)			✓	
Building envelope air permeability (0.35 h^{-1} on the ground floor, 0.17 h^{-1} at the first floor)				✓
Ventilation *via* opening of windows	✓		✓	
Balanced ventilation with a standard exchange rate of 12 l/s per person including cooling		✓		✓
Combined heating/cooling unit designed so that it looked like a flat panel radiator	✓		✓	
Centralised domestic hot water supply	✓			
Additional insulation of external walls i.e. in the kitchen area and in utility rooms		✓		✓
New insulated ground slab		✓		✓
Radiator heating on the first floor		✓		✓
Underfloor heating on the ground floor		✓		✓
Decentralised domestic hot water supply		✓	✓	✓
External solar shading with a reduction factor of 0.5				✓
Energy-saving light sources	✓	✓	✓	✓
Daylight-controlled lighting	✓	✓	✓	✓
Centralised control of electrical components	✓	✓	✓	✓
Cooling *via* a centrally placed unit where excess heat is transferred to the outside air	✓	✓	✓	✓
Shared canteen facilities	✓	✓	✓	✓
Shared meeting/conference facilities	✓	✓	✓	✓

by means of cooling. Fig. (**6**) shows the calculated heating and cooling demand of the supervisor's residence where low-energy glazing – 3 mm glass set into the existing secondary frames - was implemented.

The changed energy demand for heating and cooling was calculated to change in percentage CO_2 emissions. Calculations of the CO_2 emissions were based on CO_2 emission factors of 122, 377, 288 and 204 g/kWh for district heating, electricity, oil and gas, respectively [9].

5. RESULTS

For each building in the listed complex, individual feasible measures were agreed for its energy upgrading, see Table **1**. The calculated impacts of the individual measures on the energy upgrading are shown in Table **3**. The impacts are found by comparing calculations with the reference calculations. Measures that were included in the reference model are not shown as a single calculation showing specific energy savings. Calculated numbers for the impact of heating, cooling and electricity per m^2 and the calculated CO_2 savings is shown in Table **3** for the implementation of the individual measures, thus achieving a thermal environment in Category C.

Measures are ranked according to the achieved savings in CO_2 emissions. Measures with more than 5% CO_2 savings are highlighted for each building in the complex.

Table 2. Requirements for the thermal environment at Category C.

Thermal state of the body as a whole:		
	Predicted Percentage Dissatisfied (PPD)	< 15 %
	Predicted Mean Vote (PMV)	-0.7 < PMV < +0.7
Local discomfort:		
	Draught Rate (DR)	< 30 %
Percentage dissatisfied caused by:		
	Vertical air temperature difference	< 10 %
	Warm or cool floor	< 15 %
	Radiant asymmetry	< 10 %

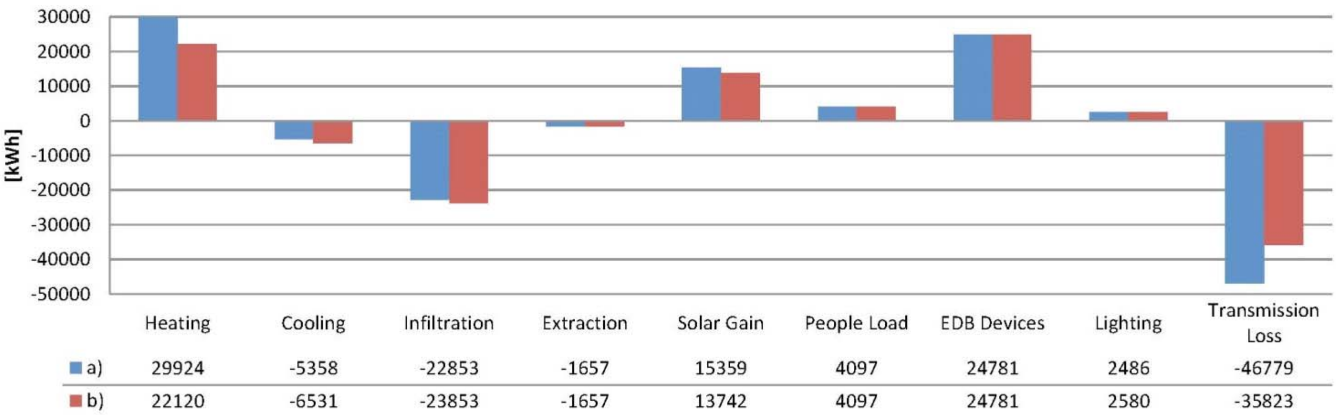


Fig. (6). Breakdown of the energy balance in the building that holds the supervisor's residence with; a) original secondary glazing; and b) where the existing secondary glazing was changed to low-energy glazing. The heat balance is based on the future interior layout with the future occupant loads and expected use of IT equipment. The thermal environment was maintained at a Category C level by means of cooling.

The former measured energy consumption per year for heating and electricity is shown in Table **4**. The calculated future energy demand for heating, electricity and cooling is also given in Table **4**. The calculated overall change of the transmission loss and the calculated overall change in CO_2 emissions, including achieving Category C for the thermal environment are shown in Table **5**. Table **5** also shows the calculated overall change in CO_2 emissions compared with the base model describing the existing conditions, interior layout and occupant loads of the individual buildings that agree with measured consumption data from the former use of the individual buildings.

6. DISCUSSION

The overall transmission loss and the CO_2 savings calculated for the reference model without measures and the reference model with the implemented feasible energy-upgrading measures shown in Table **1** were calculated. Furthermore, the CO_2 savings calculated for the base model and the reference model with implemented feasible energy-upgrading measures were calculated. The base model represents the former conditions, interior layout and occupant loads of the individual buildings prior to the energy upgrading and the new layout.

Calculated numbers for the impact of heating, cooling and electricity per m^2 and the calculated CO_2 savings are shown in Table **3** for implementation of individual measures, thus achieving a thermal environment in Category C. Ranking measures according to the achieved savings in CO_2 emissions and pointing out measures saving more than 5% CO_2 enhance measures as; additional insulation of external walls, centralised control of electrical components, building envelope air permeability and insulated new ground slab. However, these findings cannot be generalized as for the Mono-pitch roof building the measure; centralised control of electrical components does not create more than 5% CO_2 savings but in contrary measures as; low-energy glazing and new windows with low-energy creates important savings. For all buildings in the complex measures as; energy-saving light sources and balanced ventilation are seen to benefit very little to the achieved CO_2 savings or to increase the CO_2 emissions. The effect of the individual measures are hence related to the individual building, its layout and use, why a pre choice of measures cannot be made and the most relevant measures must be found for heritage buildings individually.

Table 3. Heating, cooling and electricity per m^2 heated area and the calculated change in CO_2 emissions implementing individual measures while achieving a thermal environment in Category C.

Building	Heating [W/m^2]	Cooling [W/m^2]	Electricity [W/m^2]	Change in CO_2 emission
Supervisor's residence				
Centralised control of electrical components	59.4	-8.7	45.9	-7.5%
Building envelope air permeability	37.6	13.2	51.0	-6.1%
Low-energy glazing	41.7	-12.3	51.7	-4.3%
Energy-saving light sources	57.0	-5.2	50.0	-1.3%
Half-timbered building				
Additional insulation of external walls	49.1	13.4	80.5	-12.8%
Centralised control of electrical components	111.8	10.7	70.6	-7.6%
Building envelope air permeability	71.5	-13.0	80.5	-7.6%
Insulated new ground slab	84.7	-13.3	80.5	-4.4%
Low-energy glazing	97.5	-11.3	80.8	-1.7%
New windows with low-energy	98.3	-10.8	81.8	-0.7%
Energy-saving light sources	106.4	-11.2	79.6	-0.7%
Balanced ventilation	102.9	-10.1	85.8	3.7%
Office building				
Centralised control of electrical components	143.3	-19.9	97.1	-10.8%
Building envelope air permeability	117.9	-26.9	108.8	-6.1%
Low-energy glazing	102.4	-27.3	109.1	-4.1%
Energy-saving light sources	134.0	-23.3	106.4	-1.5%
Monopitch roof building				
Additional insulation of external walls	71.9	16.4	37.4	-13.5%
Low-energy glazing	88.0	-14.5	37.6	-8.1%
New windows with low-energy	94.8	5.7	37.4	-7.3%
Building envelope air permeability	90.6	15.9	37.4	-6.8%
Insulated new ground slab	91.3	-18.6	37.4	-5.3%
Centralised control of electrical components	116.7	13.1	33.6	-3.7%
Energy-saving light sources	62.5	13.9	36.6	-0.9%
Balanced ventilation	110.4	-12.1	41.6	4.6%

Special attention is drawn to the half-timbered building and the office building. Indoor climate considerations made it necessary to add a significant cooling capacity to cool the canteen and the meeting facilities on the ground floor of the half-timbered building. This was a result of the initial planning of the complex where the half-timbered building was given a function as a service building for the other buildings in the complex. The canteen and meeting facilities were mainly to be located on the ground floor of the building, thus increasing the needed cooling capacity. The initial planning of the complex showed the need for a significant cooling load that resulted in a negative influence on the expected CO_2 savings of the half-timbered building.

Calculations showed a need for adding a substantial cooling capacity to the office building as the occupant density of this building was increased to become much higher than in the other buildings. Establishing a Category C for the thermal environment of the office building had a negative effect on the actual CO_2 savings but far less as on the half-timbered building. Compared with the former use and layout of the building, the reduction was 20%.

Calculations of the entire renovated listed complex showed a potential overall CO_2 saving of 18% compared with the former use of the complex. However, the energy needed to achieve a workspace with a Category C for the thermal environment, was seen to result in a total CO_2 saving

Table 4. Energy consumption in [MWh] per year.

	Supervisor's residence	Half-timbered building	Office building	Monopitch roof building
Former measured consumption for:				
Heating	28.39	99.44	97.09	57.78
Electricity	23.94	40.86	96.85	26.57
Calculated future consumption for:				
Heating	8.67	39.58	99.91	30.71
Electricity	22.69	64.61	68.92	22.95
Cooling	5.78	14.78	13.82	6.69

Table 5. Calculated overall change in transmission loss and change in CO_2 emissions.

	Supervisor's residence	Half-timbered building	Office building	Monopitch roof building
Transmission loss	-27%	-57%	-20%	-39%
CO_2 emissions, incl. Category C, irt. reference models	-20%	-17%	-24%	-17%
CO_2 emissions, irt.* the basis model	-6%	20%	-20%	-20%

* irt. is short for: in relation to

calculated to be 7.8% as a result of the distribution of facilities on the individual buildings. However, the indoor climate level was raised from an unacceptable level to a Category C level. By rearranging the layout, room was made for another 40 workstations.

Measurements were implemented with due respect for the core heritage values of the complex and without compromising identified heritage values.

Better results might have been obtained if canteen and meeting facilities had been placed outside the complex. It was not possible in this case, but might be a possibility in other buildings; this indicates that energy savings may only be obtained if there are limitations on the use of listed buildings.

Although this case shows synergy between the interests in preserving heritage values and energy-saving measures, it is only true for some of the measures. Unfortunately, many measures involve a conflict between the two [3]. Air tightening the buildings is one of the feasible measures in this study; since the early 1970s, it has been done to many existing buildings, e.g. by replacing old windows with new more airtight windows. This resulted in reduced energy consumption but unfortunately the humidity in many buildings also increased, creating moisture-related indoor climate problems. The reason was a biased focus on energy savings. Tightening buildings should only be done in combination with the possibility to ventilate, either automatically and preferably with heat recovery or manually where users must be aware of the necessity of actively ensuring ventilation, i.e. by opening windows regularly. Ultimately, high moisture content in wooden beam ends can result in a collapse of the beam. Mould growth is less severe at the beam end. Both failure modes should be avoided. In [10], it is recommended to install monitoring equipment connected to an automatic control system of the indoor air to reduce the humidity as needed. In [11], it is suggested to leave a 200 mm gap just above the floor, thus creating a thermal bridge that will ensure higher temperatures at the beam end compared with a fully insulated wall. In some cases, a combination of the two measures might be necessary.

Previously [12] concluded that the most important factors for the moisture conditions at the beam ends are:

- Geometry of the structure
- Interior temperature and relative humidity
- Production of interior moisture
- Outdoor climate (i.e. temperature, relative humidity, driving rain intensity and wind velocity)
- Material properties for wood and masonry
- Air changes around the beam end

As listed buildings - also when upgraded to save energy - are expected to preserve our cultural heritage for posterity, the list of feasible measures for the energy upgrading, see Table **1**, should be compared with the climate changes that are to be expected in the EU region [13]:

- More frequent and heavier rain fall
- More extreme temperatures in summer and heat waves of long duration including more hours of sun
- Warmer and more humid winters
- More frequent and heavier storms
- Extreme snowfall

Some of the changes to be expected will worsen moisture conditions at beam ends, e.g. the combination of storms and heavier rain which will result in a more intense driving rain. When the drying potential of the exterior wall is reduced by interior insulation, driving rain becomes more critical. On the other hand, more hours of sun mean higher indoor temperatures which decreases the relative humidity. Unfortunately, it also means that more cooling is needed, and as the study case shows, cooling increases the energy demand significantly.

As a result, the most sustainable solution might be to limit the use of historic and heritage buildings; to accept that some buildings are not suitable for any occupation and may never become suitable for all purposes. In some cases, it is not feasible to use a building for canteen facilities which is in humidity Class 4 according to ISO 13788 [14], but it may be possible to use it for offices (humidity Class 2). The difference is that at an outdoor temperature of 0 ºC, the indoor moisture supply is 4 g/m^3 in humidity Class 2 but 8 g/m^3 in humidity Class 4.

Finally, energy-saving measures should be reversible; it must be possible to re-install the measures and restore the building to its former state and to change the use of the buildings. In this way, the measures that seemed necessary at the time in order to make the building attractive, can be removed later, if the building needs to fulfil another purpose or at a time when energy loss and CO_2 emissions are no longer problematic.

CONCLUSION

On a global scale, measures to mitigate the effects of climate change have focused on the reduction of CO_2 emissions. Tightened requirements to energy loss and the thermal standard of new buildings mean that existing and especially heritage buildings possess a very low standard compared with today's requirements for new buildings. Many existing buildings and heritage buildings have heritage values that need to be protected while the buildings need to remain part of the attractive building stock. Therefore, it is important to assess the impact of heritage buildings on climate change impacts while not compromising heritage values. The study of the extensive energy-upgrading of a listed complex, *Fæstningens Materialgård*, has shown feasible energy-upgrading measures and quantified the reduced CO_2 emissions. It demonstrates that it is possible to improve the energy performance and indoor climate of heritage buildings while not compromising identified heritage values, and ensuring that they remain part of the attractive building stock. However, the cost of implementing the energy-upgrading measures was not quantified as this case study was carried out as a pilot project to identify feasible energy-upgrading measures and to quantify the reduced CO_2 emissions.

The benefits of individual measures are shown to be related to the individual building in the complex, according to its layout and use why a pre choice of measures cannot be made. The most relevant measures must be found for heritage buildings individually.

Calculations of the entire renovated listed complex showed a potential overall CO_2 saving, calculated for the base model and the reference model, of 18%. However, the energy used to achieve a workspace with the classification of Category C for the thermal environment [8], was seen to result in a total CO_2 saving, calculated to be 7.8%. However, the indoor climate was raised from an unacceptable unclassified level, to a Category C level. By rearranging the layout, room was made for another 40 workstations. Furthermore, measurements of the building envelope permeability showed that establishing an airtight building envelope is one of the main issues when energy upgrading heritage buildings. Apart from resulting in a large heat loss, air infiltration also causes indoor climate discomfort in the form of draughts and asymmetrical temperature distribution in individual buildings.

The renovation and energy upgrading of the listed complex, *Fæstningens Materialgård*, have shown that the primary planning, including the function of a heritage building, is crucial to the gained energy and CO_2 savings. Especially, the location of service facilities like the canteen and meeting facilities is important. These facilities can cause a significant cooling load that might influence the expected savings in CO_2 negatively. At the same time, the use of a listed building should be considered, as some energy-saving measures result in higher moisture levels at critical parts of the building. The consequence might be a moulding growth or even deterioration of structural parts. As listed buildings per definition are expected to be preserved for posterity, expected climate changes must also be taken into consideration when energy-saving measures are chosen.

CONFLICT OF INTEREST

The authors confirm that this article content has no conflict of interest.

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